Trends in Optocoupler Radiation Degradation

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***Abstract* – Proton radiation test results for new optocoupler technologies are compared with those of older optocouplers. The new devices are far more resistant to displacement damage effects, and also have much higher current transfer ratio (CTR). The improvements are due to improved optical coupling efficiency in combination with LED technologies that are inherently more resistant to lifetime degradation. Because of these changes, CTR degradation is no longer dominated by LED damage; LED degradation, gain degradation, and photoresponse degradation all contribute to the overall changes in CTR after irradiation in the newer device types.**

I. INTRODUCTION

Optocouplers are simple devices compared to conventional integrated circuits, but have proven to be somewhat difficult to use in space because they require high internal gain to amplify photocurrent produced by internal light-emitting diodes (net power transfer from the LED to the photodetector is on the order of 0.1%). Space failures have occurred from two different mechanisms: displacement damage from high-energy protons, that produces permanent degradation [1-7]; and transient upsets from heavy ions or protons [8,9]. Transient upset effects are generally important only for optocouplers with high-gain amplifiers, and are expected to be of secondary importance for the devices in this paper compared to permanent degradation. Therefore, transient effects are not addressed in the present paper.

Several advances have been made in optocoupler technology that improve performance and reduce input current by more than an order of magnitude. The purpose of the present paper is to evaluate proton damage in new optocoupler technologies and compare their radiation response with results for older optocouplers.

Four devices were selected for the study. Some of their key properties are shown in Table 1. Two new optocouplers from Agilent Technologies, the 6N139 and HCPL4701, were evaluated. They are designed to operate with unusually low input currents – as low as 40 μA – with Darlington phototransistors for amplification. Their radiation response will be compared with the older 4N49 optocoupler, which uses a simple phototransistor that is laterally coupled to an amphoterically doped LED [2], with an input current of 1 mA or more.

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As shown in the table, the 6N139 and HCPL4701 have much higher current transfer ratio than older optocouplers. Both devices are low-speed, low power parts with open collector outputs, and do not incorporate high-gain amplifier circuits. A special high-linearity optocoupler, the HCNR200, which provides matched photocurrents in two photodiodes from a single internal LED, was also selected for the study. All three of the new optocouplers use double-heterojunction LEDs. Tests were also done on several lots of the older 4N49 optocoupler (manufactured by Micropac) in order to determine how the radiation response of this highly sensitive device, which continues to be used in space systems, has varied over a production period of about 7 years.

Table 1. Properties of the Optocouplers Used in the Study

Device	Manu-facturer	Input Current (mA)	Current Transfer Ratio	LED Technology
6N139	Agilent	0.5	20	Double-Het.
HCPL4701	Agilent	0.04	35	Double-Het.
HCNR200	Agilent	0.1 -10	0.005*	Double-Het.
4N49	Micropac	1	2	Amphoteric

*The HCNR200 contains no active gain elements. The current transfer ratio is the ratio between current in either of the two photodiodes to the forward current of the LED.

II. DISPLACEMENT DAMAGE TESTS

A. Experimental Approach

Radiation testing was done using 50-MeV protons at the University of California, Davis cyclotron. Devices were irradiated with all pins at ground. They were removed after each exposure run, which took approximately 5 minutes to complete, to measure their electrical properties. Measurements included current transfer ratio (CTR), transistor gain, and special measurements of the photoresponse (essentially the photocurrent in the collector-base region of the phototransistor or photodiode). Photoresponse basically eliminates transistor gain from CTR, but does not include corrections for LED degradation. When measured in this way, photoresponse is essentially the product of the detector responsivity and the LED output power.

An Agilent Technologies 4156B parameter analyzer was used to make the measurements, programming the system to enable measurements with an 80 μs pulse length. This limited the total charge during a measurement sequence to less than 0.1 mC when a series of current steps was used to measure current transfer ratio (see Figure 1). This was done to reduce interference from injection-enhanced annealing in the light-emitting diode [10,11]. Devices were placed in a temperature controlled test fixture during measurements that held the device temperature to 22 ± 0.1 °C to reduce interference from temperature fluctuations over the course of the experiment.

B. Results for Optocouplers with Low Input Current

The degradation of the two Agilent optocouplers with low input current was very similar. Figure 1 shows results for the HCPL4701, taken over a range of input currents. The data correspond to the mean of six different devices from the same lot. Several features should be noted. First, CTR varies over a wide range, depending on the LED input current. Second, the CTR of these devices is much higher than that of conventional optocouplers. Third, these devices are far less affected by radiation damage than the older 4N49 optocoupler (see the dashed line in Figure 2), in spite of the higher CTR and very low LED input current of the new devices.

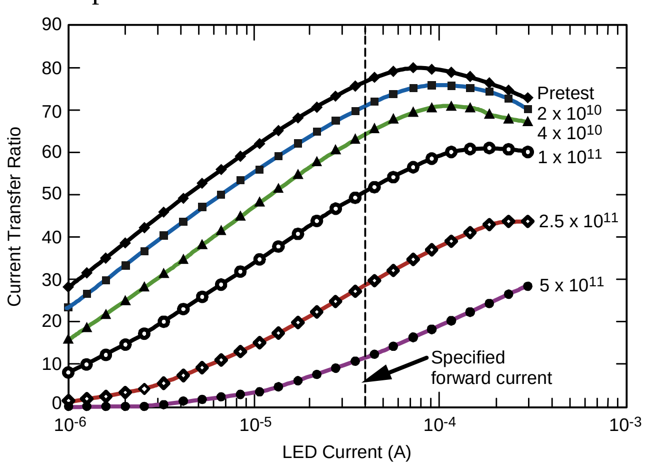

Figure 1. Current dependence of CTR before and after irradiation for the HCPL4701 optocoupler.

The efficiency of the phototransistor depends on optical power, which is the reason that the CTR increases with increasing forward current through the LED. After irradiation, the light output of the LED is reduced. This causes the current at which the CTR "peaks" to move to higher forward current values as the part is irradiated to successively higher radiation levels. Thus, the current dependence of transistor gain also affects CTR degradation; for operating current below the peak current region the current dependence will add to CTR degradation because the operating current will decrease as the LED light output degrades.

However, for forward currents above 100 μA, the phototransistor will initially operate above the peak current, reducing its gain. This will reduce the relative degradation in CTR at lower radiation levels because the operating current will decrease when the LED power decreases, moving the phototransistor operating point closer to the peak current, where it has higher gain. Once the operating current reaches the peak gain region, further degradation of the LED will have a relatively higher effect on current transfer ratio because the gain of the phototransistor then decreases as the operating current is reduced.

Figure 2 shows degradation of CTR, photoresponse and transistor gain (normalized) for the HCPL4701 optocoupler vs. proton fluence.* CTR was measured with a forward current, I_F, of 40 μA, the value specified by the manufacturer.

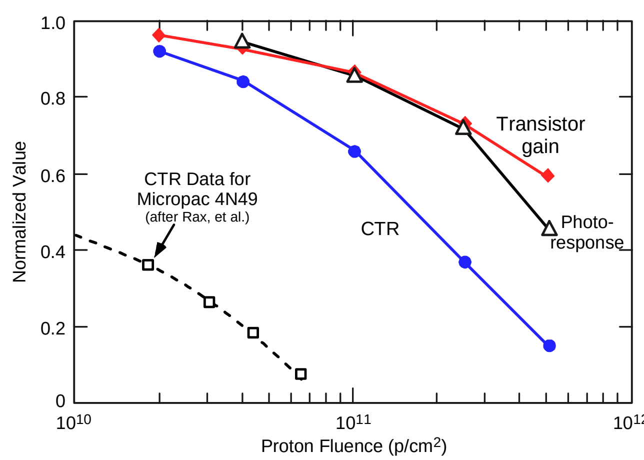

Figure 2. Degradation of CTR, transistor gain and photoresponse for the HCPL4701 optocoupler.

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*Older results for the Micropac 4N49 [2] are included in Figure 2 for comparison. Degradation in the 4N49 is dominated by the LED, but the LED technology used in the HCPL4701 is much harder. Consequently, CTR degradation in the HCPL4701 is affected by degradation of the LED, phototransistor gain, and the photocollection efficiency.

Transistor gain and photoresponse degradation are nearly identical for fluences up to 3 x 10^{11} p/cm^2. Thus, both factors contribute to CTR degradation. That was not the case for the 4N49, where CTR degradation was dominated by LED degradation [2]. CTR degradation is nearly the same as the product of transistor gain and photoresponse degradation when the current dependence of CTR is taken into account.

Results for the 6N139, which has a higher input current rating, were similar to the results for the HCPL4701 as shown in Figure 3. However, the CTR degradation is approximately a factor of two less for the 6N139 at the highest fluence. The improvement is not due to optical efficiency (see the Discussion section), but is caused by the higher light output of the LED. This raises the operating current of the phototransistor into a region where it operates more efficiently, reducing the relative amount of degradation compared to the HCPL4701.

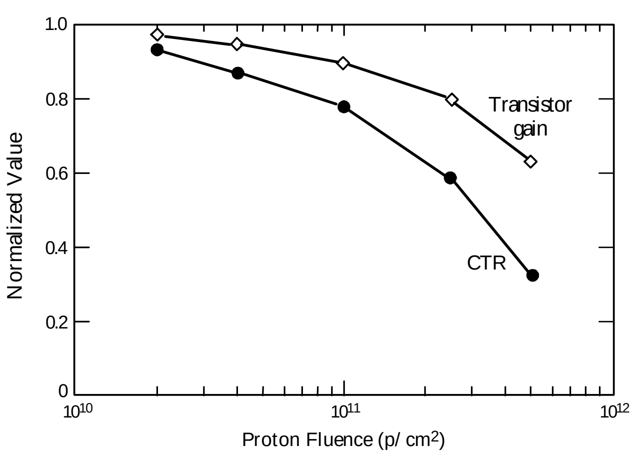

Figure 3. CTR and gain degradation for the 6N139 optocoupler

The current dependence of CTR for the 6N139 is shown in Figure 4. Initial values of CTR at low forward current are much lower for that device compared to the HCPL4701 (Figure 1). Although proton degradation in the two devices is similar, the 6N139 cannot operate over the broad range of input currents that is possible for the HCPL4701. The difference in current dependence is probably due to higher collector current in the phototransistor of the 6N139. The phototransistor operates above the peak current if the input current is much above the specification value of 0.5 mA. The maximum LED input current is 20 mA, which would force the operating point into a heavily saturated region. Thus, this device is really only intended for operation at LED currents below about 2 mA.

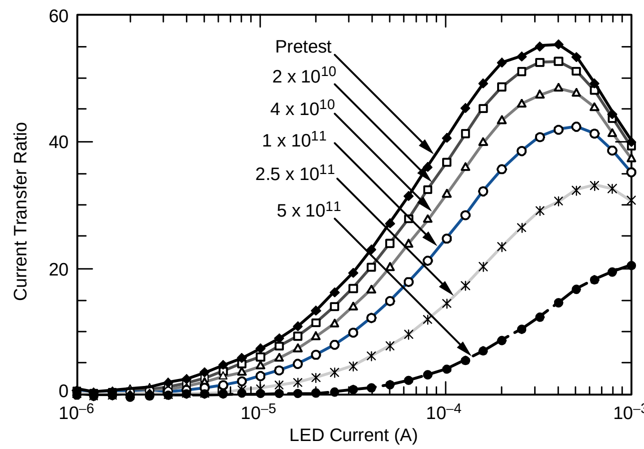

Figure 4. Current dependence of CTR before and after irradiation for the 6N139 optocoupler.

C. Results for the Linear Optocoupler

The HCNR200 linear optocoupler has two basic photodiode detectors, driven by light from a single LED. It contains no phototransistors. Measurements of the photodiode current show how the overall photoefficiency of the optocoupler changes with radiation without the added complication of phototransistors. The effective CTR is quite low, about 0.005, but the key design parameters for that device are matching of photocurrent in the two photodiodes, and maintaining linearity over a wide range of currents.

Figure 5 shows how photocurrent in this device is affected by radiation. Degradation of this device is very similar to CTR degradation in the HCPL4701 (Figure 2), and is dominated by LED degradation, although photoresponse degradation also plays a role.

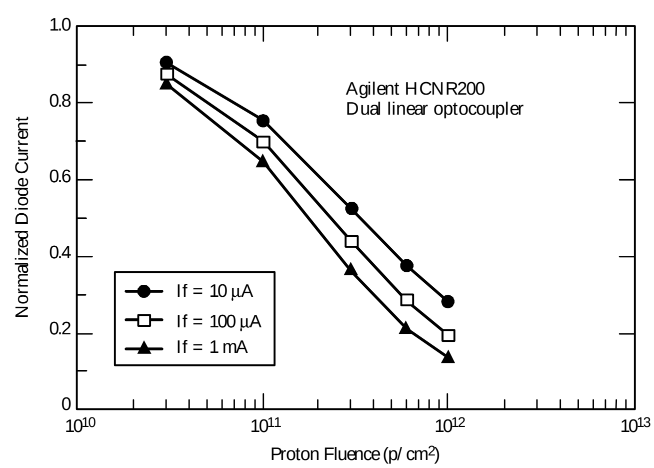

Figure 5. Degradation of photoresponse of the HCNR200 linear optocoupler (each side of this dual device degrades nearly identically).

Most LEDs have somewhat lower degradation when they are operated at higher currents [2,6]. However, photoresponse degradation of the HCNR200 shows slightly more degradation when the device is operated at higher currents. This may be due to the fact that photoresponse measurements do not measure LED output directly, but also include photoefficiency, which is also current dependent. The design of this particular device – which emphasizes close matching of photocurrents of the two diodes instead of overall optical efficiency – may also be a contributing factor.

Matching is a critical parameter for most circuit applications of this device. Figure 6 shows the mismatch of the mean and worst device for a sample of five devices, measured with $I_F = 10\ \mu A$. The photocurrent of the two photodiodes remained closely matched, even after very high radiation levels.

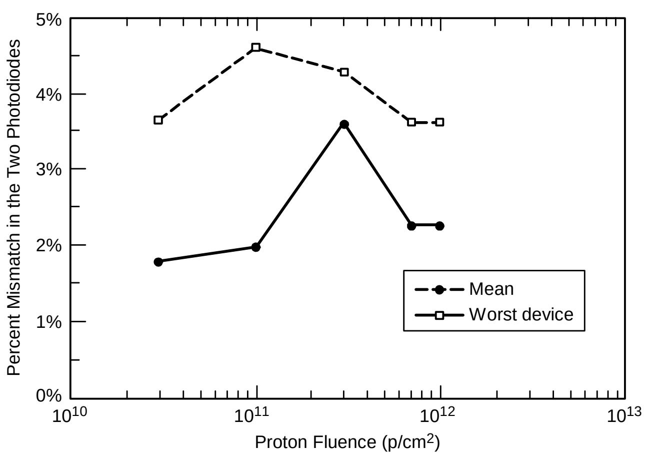

Figure 6. Matching of the two photodiodes in the HCNR200.

D. Results for the 4N49

The 4N49 has been frequently used in space systems even though it is extremely sensitive to proton displacement damage. Figure 7 shows the normalized degradation of CTR, photoresponse, and transistor gain for a recent lot of devices from Micropac. Transistor gain (measured at a collector current of 1 mA) is affected very little, and consequently CTR degradation is dominated by LED degradation. CTR actually degrades somewhat faster than photoresponse. The reason for this is the decrease in operating current of the phototransistor as the LED output power is degraded. That reduces the operating current of the phototransistor to the point where it is less efficient. The peak gain of the phototransistor in the 4N49 occurs at currents that are considerably greater than the operating current with $I_F = 1$ mA, increasing the importance of the current dependence of transistor gain in the overall performance of that device type. Even though (electrical) gain degradation at fixed injection changes very little (measured *electrically* with external base current), the response of the optocoupler is markedly affected by the decreased injection level that occurs as the LED degrades.

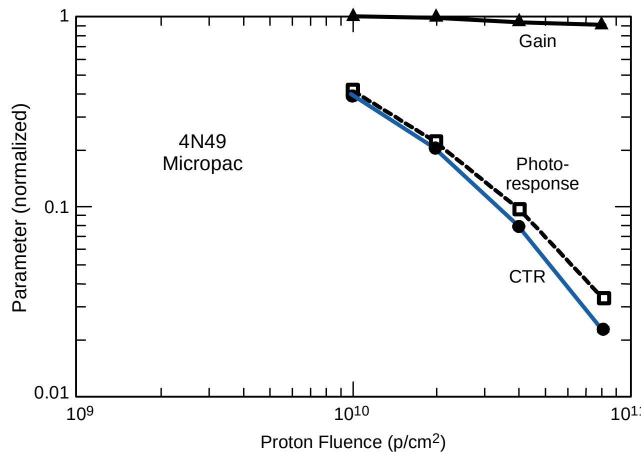

Figure 7. Normalized CTR, photoresponse and gain vs. proton fluence for Micropac 4N49 optocouplers (Date Code 0139).

III. Discussion

A. Degradation of the New Optocoupler Devices

Agilent Technology uses double-heterojunction LEDs, which are less affected by displacement damage compared to the amphoterically doped LEDs used in older optocouplers [11]. The marked improvement in radiation hardness of the low input current optocouplers is due to two factors: the LED technology and the circuit design. The 4N49 optocoupler uses a single phototransistor, but the Agilent devices use the Darlington configuration shown in Figure 8.

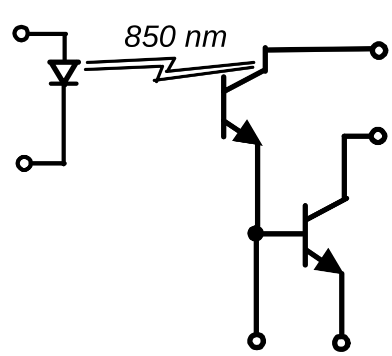

Figure 8. Darlington transistor configuration used for the 6N139 and HCPL4701 optocouplers.

The first transistor, which is also the photodetector, is connected as an emitter follower. This increases photocurrent by the factor h_{FE}, which increases base current in the second transistor by the same factor. Photoresponse measurements cannot be made on the first Darlington transistor with the normal pin configuration, but can be made on the second transistor. However, the currents are increased by the factor h_{FE}. That is not the case for the HCNR-200; it uses a basic photodiode.

The ratio of the photoresponse measurement to the LED current of the different types of devices is shown in Table 2. This table does not take the optical efficiency of the LED into account, but it clearly shows that the overall optical-to-electrical efficiency of the new types of optocouplers is substantially improved compared to the older optocoupler types. The overall photoresponse of the HCNR-200 is about five times better than that of the 4N49, taking into account that the LED current is split between the two photodetectors in the dual assembly.

Table 2
Coupling Efficiency of the Four Types of Optocouplers

Device	LED Current (mA)	Ratio of Photoresponse to LED Current
HCPL-4701	0.04	0.36
6N139	0.5	0.29
HCNR-0200	1	0.0021
4N49	1	0.00084

The Agilent optocouplers use a sandwich construction method that increases the coupling efficiency, while the 4N49 uses a configuration where the LED assembly is mounted alongside the phototransistor, relying on a polymer coating for light coupling [2].

B. Annealing

Although some annealing may also occur in phototransistors, annealing in light-emitting diodes usually dominates annealing effects in optocouplers when they are operated near room temperature. Annealing in LEDs is strongly injection dependent. It has been shown that LED damage remains stable over periods of several months for unbiased devices at room temperature [11], even for LEDs that are strongly affected by injection-enhanced annealing. However, once forward current is applied to the LED, the annealing process begins. Older work on discrete LEDs has shown that a current-time product (charge) of about 0.01 C is sufficient to cause significant annealing for LEDs with a maximum forward current rating of 100 mA. Optocoupler measurements need to be planned to take this sensitivity into account. Although annealing may ultimately help in space applications, it is effectively an interference during characterization measurements, and can lead to inconsistent results.

Annealing effects depend on the construction and operating characteristics of the LED. For example, earlier work on proton damage in discrete double-heterojunction LEDs indicated that they anneal very little unless they are operated with very high input currents [6,11]. The same work showed that amphoterically doped LEDs are strongly sensitive to injection-enhanced annealing effects.

Annealing experiments were done for the 6N139 optocoupler to determine how newer technology devices from Agilent Technology compared with annealing data for older device types. These experiments were done using a forward LED bias of 5 mA at room temperature after the device was irradiated to 5×10^{11} p/cm^2. The maximum average input current rating is 20 mA, so a forward current of 5 mA corresponds to a high-injection level for this device.

Annealing was determined by measuring photocurrent in the collector of the first transistor in the Darlington phototransistor, eliminating the second transistor in order to reduce the operating current of the phototransistor when the LED was operated with I_F = 5 mA. This reduced power dissipation in the phototransistor. The devices for the annealing study were irradiated to a fluence of 5×10^{11} p/cm^2. Collector current in the first transistor was reduced by a factor of 3.1 after irradiation compared to values before irradiation.

As shown in Figure 9, about 16% of the photocurrent in the transistor recovered over a time period of about two days. Although some of the damage recovers, the current was initially 3.1 mA prior to irradiation, and thus only a small fraction of the damage recovers. For comparison, annealing studies of amphoterically doped LEDs show nearly a factor of two recovery in damage under similar conditions [6,11]. Thus, although some annealing takes place in these devices, the results agree with earlier studies of discrete double-heterojunction LEDs that show relatively slight annealing.

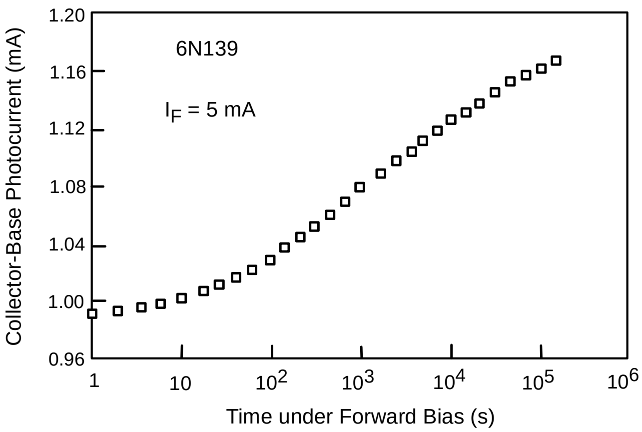

Figure 9. Annealing data for the 6N139 optocoupler using a forward bias of 5 mA.

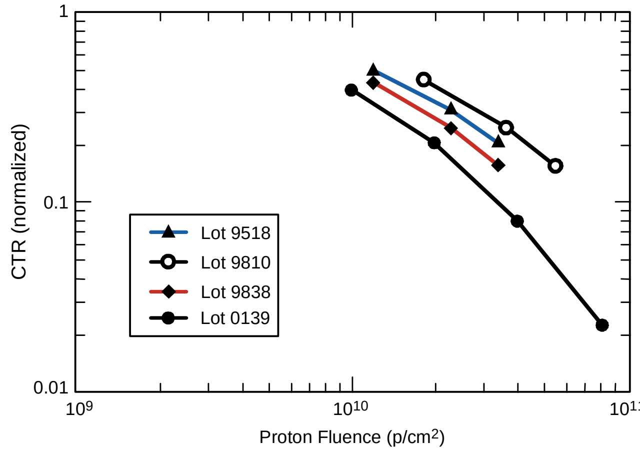

Figure 10. Normalized CTR degradation for various lots of the Micropac 4N49 over a seven-year time period. The LED current was 1 mA.

C. Performance of the Micropac 4N49 over Extended Time Periods

Previous work showed that degradation in older versions of the 4N49 optocoupler was dominated by degradation of the internal light-emitting diodes [2], which are amphoterically doped. Amphoterically doped LEDs are very efficient [12], but they are extremely sensitive to displacement damage because of the broad transition region from p- to n-material that is formed by gradually altering the temperature during the growth phase. Consequently, these devices require long carrier lifetimes for operation, which is the reason they are so strongly sensitive to displacement damage.

A comparison of degradation of several lots of 4N49 devices is shown in Figure 10. The data were taken for I_F = 1 mA, the recommended forward current for the JANTX version of the part. There is considerable difference in the radiation sensitivity of different lots, and this appears to be related to the light-emitting diodes, based on previous work with discrete LEDs and phototransistors as well as photoresponse and gain measurements that were made on the more recent 4N49 lots. The date codes span a seven-year time period.

The lot with the best performance had much higher CTR values (the mean CTR with I_F = 1 mA was above 10 for that lot, even though the minimum guaranteed CTR is 2). The increase in CTR allows the phototransistor to operate in a more efficient region, reducing the effect of current dependence of transistor gain as the LED output degrades. The photoresponse, which was measured for three of the four lots, was also higher for the lots with better radiation performance.

The interplay between light output and radiation damage is cause for concern, because a device with reduced initial light output will be considerably more sensitive to displacement damage degradation than the rest of the devices within a device lot. This is particularly the case for the 4N49, where LED degradation dominates, because the phototransistor is forced to operate at very low collector current with reduced efficiency for devices with lower initial light output. As shown in Figure 7, the LED power output can decrease by a factor of 10 or more at a proton fluence of 4 x 10^{10} p/cm^2. Electrical screening to eliminate devices with low initial CTR can reduce the variability of devices within a lot by eliminating devices from the population that cause the phototransistor to operate at low current, where the overall photoefficiency is reduced.

VI. Conclusions

This paper compared radiation damage in a new series of basic, open-collector optocouplers with that of older devices. These new device designs have much higher current transfer ratios compared to the older 4N49, and can be irradiated to levels that are more than a factor of ten higher than the 4N49 before significant degradation occurs in a proton environment.

Gain and photoresponse degradation were similar for the new optocouplers and the older 4N49 devices, providing direct evidence that LED degradation is the main reason for the improved radiation performance.

Analysis of the results and comparison with a more elementary type of optoisolator in this same series of devices shows that the increased CTR is due to the circuit design, which incorporates a Darlington transistor. The improved radiation performance occurs because the Agilent devices use double-heterojunction LEDs. Even though one of the devices uses very low drive current – 40 µA – it is still at least an order of magnitude more resistant to proton damage than the 4N49, which requires a drive current of 1 mA. Thus, these devices are promising candidates for space applications.

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